Efficient parametric terahertz generation in quasi-phase-matched GaP through cavity enhanced difference-frequency generation

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We report an efficient parametric terahertz (THz) source by using bonded quasi-phase-matched (QPM) GaP crystals pumped by the C-band pulsed fiber lasers in a master oscillator power amplifier configuration, based on difference frequency generation (DFG). We observed that the QPM-GaP crystals can effectively increase the THz generation power and efficiency by increasing the number of periods. Moreover, we observed external cavity enhanced THz DFG by placing the QPM-GaP crystal in an external ring cavity. The THz cavity enhancement factor of approximately 250 has been achieved in comparison with a single-pass THz DFG. The maximum THz average power can reach 339 μW, corresponding to a power conversion efficiency of 2.43×10^{-4} and a quantum efficiency of 3.16%. © *2011 American Institute of Physics*. [doi:10.1063/1.3571550]

Terahertz (THz) frequency radiation has been used for spectroscopy, imaging, and direct studies of molecular vibrational and rotational states.[1,2] In order to increase the sensitivity and spectral resolution of THz systems narrow bandwidth and tunable sources are critical in these fields. Among current optical methods for solid state monochromatic THz sources,[1–14] tunable THz sources based on parametric processes using nonlinear optical (NLO) crystals and nanosecond transform limited pulses is one of the most promising sources for high resolution THz sensing owing to its narrow linewidth, high spectral power density, and tunability. Difference frequency generation (DFG) involving the mixing of two narrow band pulses is an important and simple approach toward creating a monochromatic tunable THz source. DFG has the advantage of narrow linewidth and wide tuning ranges based on low loss and phase matched NLO crystals and tunable pump lasers. The choice of which NLO crystal to use depends strongly on the nonlinear coefficient, phase matching, and absorption properties of the crystal in the pump and THz frequency regions. Bulk NLO crystals suitable for THz DFG mainly include $LiNbO_3$, $ZnGeP_2$ (ZGP), GaSe, GaP, and 4-N,N-dimethylamino-4′-N′-methyl stilbazoliumtosylate (DAST).[1,3,6,11,14,15] Recently, quasi-phase-matched (QPM) crystals have attracted more interest for high power THz generation based on zinc-blende crystals, such as GaAs and GaP.[4,7,8] In this letter, we report a 339 μW monochromatic THz source based on external cavity enhanced DFG in bonded QPM-GaP crystals pumped by monolithic pulsed fiber lasers in the C-band.

Previously, tunable THz DFG was achieved in bulk GaP with $\sim$1 μm pump sources enabling a tuning range from 0.106 to 4.22 THz.[6] In this experiment, we use bonded QPM-GaP crystals with different periods in order to achieve high power THz generation. In addition, GaP has no two-photon absorption at our pump wavelength ($\sim$1.5 μm) and a second order nonlinear coefficient $\chi^{(2)}$ of $d_{14}\sim30$ pm/V.[16] Insets of Fig. 1 show the pictures of the bonded QPM-GaP crystals with different numbers of layers of coherence length thickness. They were created using an adhesive free diffusion bonding method then AR coated for the pump wavelength. The coherence length is 551.5 μm based on GaP index dispersion,[6,7] when using 1550 and 1538 nm pulsed fiber laser pumps to generate a difference frequency of 1.5 THz. Two temporally overlapped pulsed ($\sim$80 ns, 20 kHz) fiber lasers in a master oscillator power amplifier (MOPA) configuration are combined using a polarizing beam splitter and then focused into QPM-GaP crystal for the single-pass THz generation using a similar experimental setup as shown in Ref. 15. The two pulsed fiber lasers in MOPA are realized by directly modulating two single-frequency fiber lasers (1550 and 1538 nm) which have transform-limited linewidths. The pulse energy is easily scalable while maintaining transform-limited linewidth and a diffraction-limited beam quality based on our developed large core single-mode highly Er/Yb codoped phosphate fiber in the power amplifier stage.[15] Fig-

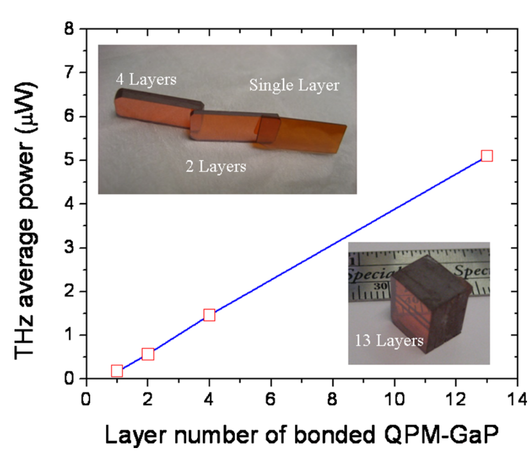

FIG. 1. (Color online) Generated THz average power based single-pass DFG for different bonded QPM-GaP crystals. Insert: pictures for single layer GaP and bonded 2-layer, 4 layer and 13-layer QPM-GaP crystals.

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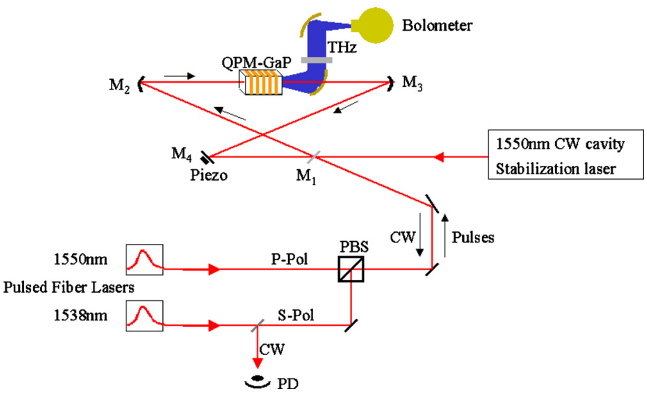

FIG. 2. (Color online) Experimental setup for cavity enhanced difference frequency THz generation. M_1, cavity coupler; M_{2-3}, cavity curved mirrors; M_3, dielectric mirror; PD, photodiode detector; S-POL, S polarization direction; P-POL, P-polarization direction; PBS, polarization beam splitter/combiner.

ure 1 shows the single-pass DFG THz average powers for different bonded QPM-GaP crystals when using orthogonal polarization directions and a 53.3 μJ pulse energy for two pulsed fiber laser pumps. The linear fit instead of the theoretical quadratic dependence is expected from the scattering loss at imperfect bonding interfaces between layers as well as pump and THz absorption. One can see that the generated THz average power for 13-layer bonded QPM-GaP is about 5.1 μW, which is 29 times higher than that for single layer GaP with coherence length, and corresponds to a conversion efficiency of 4.78×10^{-6}.

Recently, a method to produce single frequency THz radiation by enhancing and recycling nanosecond fiber laser pulses in an external ring cavity with an intracavity ZGP was reported.[11] In this letter we report a large increase in cavity enhancement and average output THz power using QPM GaP. To achieve a large cavity enhancement for two separate input beams a simple cavity is vital to reduce aligning complexity. The previously used crystal (ZGP) is birefringent and to phase-match at ~1.5 μm perpendicular polarizations are needed, which created a walk off of the two orthogonal pumps beams. This necessitated using intracavity edge filters to separately align each wavelength increasing complexity and cavity losses. By employing QPM-GaP in the external cavity the alignment has been significantly simplified compared with the system of Ref. 11.

The optical cavity is arranged in a bow tie shape as seen in Fig. 2 with a total length of approximately 0.65 m. It is stabilized by a third (1550 nm) cw laser traveling the opposite direction around the cavity then picked off by an edge filter to avoid destabilizing fluctuations in the locking signal from the nanosecond pulses. The QPM-GaP crystal is located at the waist between two curved mirrors $M2$ and $M3$ with a radius of curvature of 0.25 m. Two input couplers $M1$ (17%, 8%) were used to impedance match the cavity loss depending on which crystal was used (2 and 4 layers QPM-GaP crystals). The cavity is pumped by two temporally overlapped pulsed fiber lasers in a MOPA configuration at 20 KHz. They are combined in a polarizing beam splitter and mode matched to the cavity. All three lasers are very stable (<10 MHz over 5 min) and enhancement is achieved by tuning the two pump lasers to a resonance of the stabilized cavity. The generated THz radiation is collected and focused onto a calibrated bolometer for detection by two parabolic mirrors shown in Fig. 2.

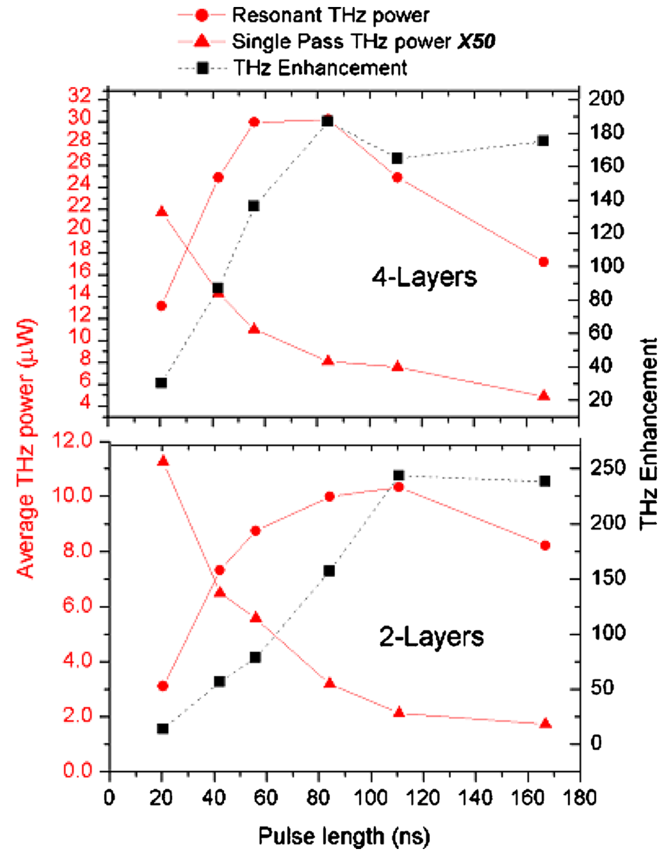

FIG. 3. (Color online) Cavity enhanced THz power, single-pass THz power (multiplied by 50) and cavity enhancement factor for two and four layers of QPM-GaP crystals when using the fixed fiber laser pulse energy of 18.3 μJ and different pulse widths.

For a given intracavity QPM crystal there is a trade-off between the number of periodic layers and the losses they incur inside the cavity in order to achieve highest THz average power.[11] In addition, for an optical cavity and associated losses there is an optimum pulse width that optimizes input peak power for efficient THz DFG and resonant pulse enhancement where they scale as inverse and proportional, respectively, to the pulse width. We chose to test this by measuring THz enhancement for different pulse widths with 2 and 4 layers of QPM-GaP crystals as seen in Fig. 3. The different pulse widths (20–170 ns) all had geometric mean pulse energies of 18.3 μJ of the two laser channels and similar pulse shapes. A peak can be observed in the overall THz average power at ~110 ns for the 2-layer sample and ~80 ns for the 4-layer sample. The difference in the pulse widths needed to achieve peak power is due to the higher losses in the 4-layer sample leading to lower pulse enhancement which favors shorter pulse lengths with higher peak powers.[11] Figure 3 also includes the cavity enhancement factors and single-pass THz output powers when using the fixed fiber laser pulse energy of 18.3 μJ and different pulse widths. One can see that the cavity enhancement factor increases when the pulse width increases. For 2-layer and 4-layer QPM-GaP crystals, the cavity enhancement factors can be up to ~250 and ~190 when the pulse width increases to ~110 ns and 80 ns, respectively. For the single-pass cases, the generated THz power decreases with increasing

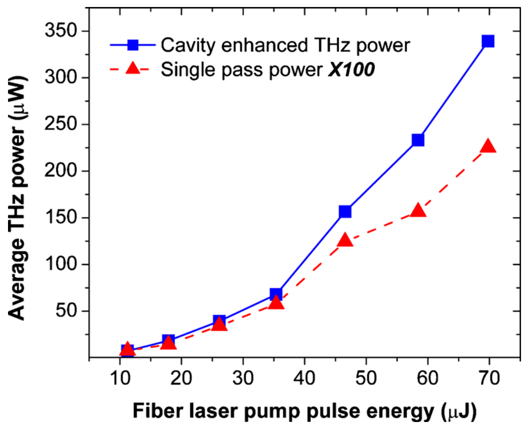

FIG. 4. (Color online) Cavity enhanced and single pass THz power vs pump pulse energy when using pulse width 80 ns at 20 kHz repletion rate.

pulse widths due to the pump peak power decreasing. A 13-layer GaP sample was also tested for the cavity enhanced THz DFG but the resulting transmission loss was too high to achieve a more efficient cavity enhancement. It is possible that more QPM layers will result in a higher cavity enhanced THz power due to the longer QPM interaction length but, as demonstrated in Ref. 11, the cavity enhancement factor is very sensitive to the cavity loss.

We then chose to use the optimum pulse width of 80 ns for the 4-layer QPM-crystal in order to achieve the highest cavity enhanced THz output power by using higher pulse energies for the pulsed fiber laser pumps in Fig. 2. Figure 4 shows the average THz powers for cavity enhanced single-pass cases when using different pulse energies up to 70 μJ with pulse widths of 80 ns. We can see that both the single pass and resonantly enhanced data follow a quadratic curve as would be expected in a second order nonlinear interaction. From a quadratic fit of the data we can see an enhancement of 151 times over the single pass case. The maximum external cavity enhanced THz average power can reach 339 μW and a peak power of ~212 mW when the pump pulse energy is approximately 70 μJ. This maximum THz output power corresponds to a THz power conversion efficiency of 2.43×10^{-4} and a quantum efficiency of 3.16%. The pulsed fiber laser pumps used were transform-limited, and the expected linewidth was 10 MHz.[2,15] Due to the parametric process (DFG), the generated THz waves are expected to have the same narrow linewidth level. So, the spectral power density for the generated THz signal can be up to ~33.9 W/THz.

In conclusion we have shown the THz generation enhancement by the use of bonded QPM-GaP crystals. In particular, we have observed efficient THz generation by combining the QPM-GaP crystal and a simple external ring cavity. In addition we optimized both the cavity losses and pulse lengths to achieve maximum enhancement. The achieved maximum THz average power can reach 339 μW, corresponding to a THz power conversion efficiency of 2.43×10^{-4} and a quantum efficiency of 3.16%.

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